

Design and Optimization of the Spallation Neutron Source



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Outline



- Introduction
- Design Philosophy
- Linac Optimization
 - Design choices
 - Design challenges
- Ring Optimization
 - Choice of accumulator ring
 - Choice of FODO-doublet lattice
 - Design challenges
- Summary

Mega Watt Facility Comparison



	Energy [GeV]	Current [mA]	Rep.-rate [Hz]	Ave. power [MW]	Type
SNS	1	2	60	2	LAR
ESS	1.33	1.9	50	2.5x2	LAR
JKJ	3	0.33	25	1	RCS
CERN PD	2	2	100	4	LAR
RAL PD	5	0.4	25	2	RCS
FNAL PD	16	0.25	15	2	RCS
EA	1	10 -- 20	CW	10 -- 20	cyclotron
APT	1.03	100	CW	103	linac
TRISPAL	0.6	40	CW	24	linac
ADTW	0.6 - 1.2	20 -- 50	CW	> 20	linac
μ -collider driver	30	0.25	15	7.0	RCS

Spallation Neutron Source



- 60 Hz repetition rate, 2×10^{14} per pulse, 2 MW proton facility
- In its 3rd year of a 7-year construction cycle
- H- Source, RFQ, DTL, CCL, SRF linac, Accumulator ring

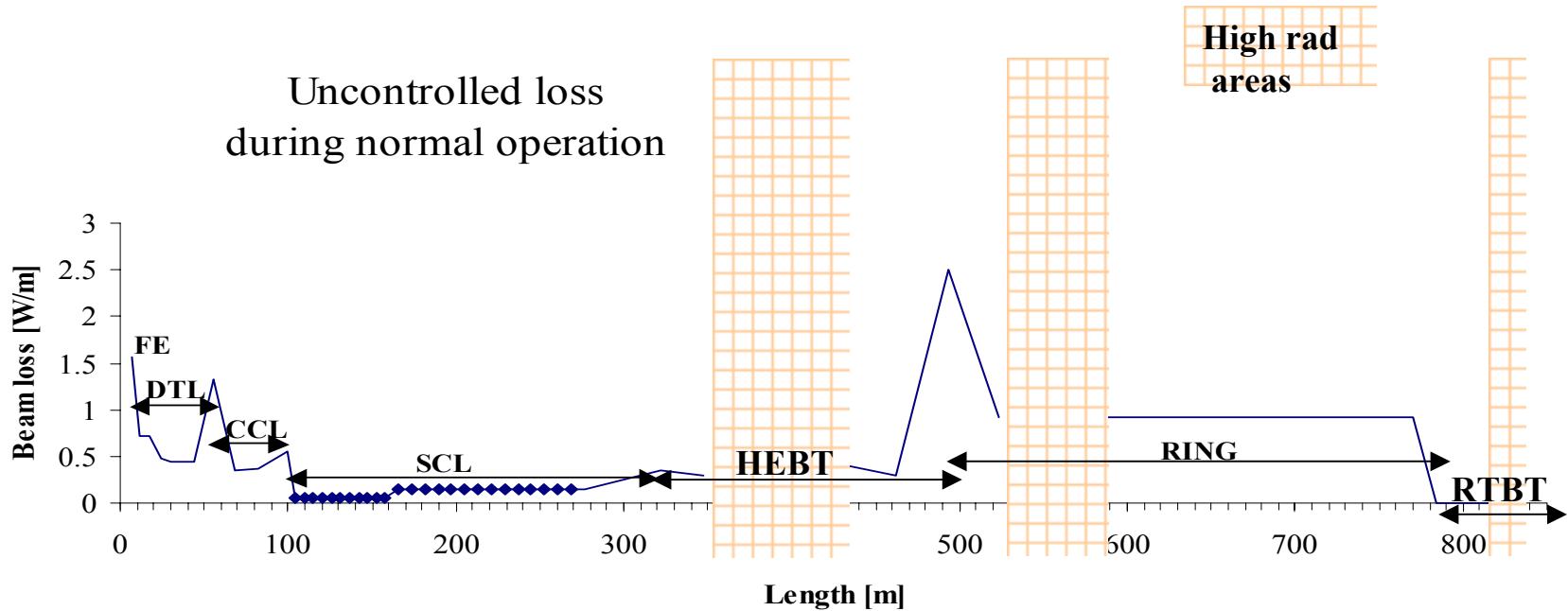


Primary Concern:

Uncontrolled Beam Loss



- Hands-on maintenance: no more than 1 mSv/hour residual activation (4 h cool down, 30 cm from surface)
- 1 Watt/m uncontrolled beam loss
- Less than 10^{-6} fractional beam loss per tunnel meter; 10^{-4} for ring



Loss & activation (expected)



Item	Controlled loss	Uncontrolled loss		Beam-off residual	Beam-on	
	(fractional)	(fractional)		activation [rem/h]	heat load	damage [rad/h]
	(integral)	(integral)	(loss/meter)	(4 h down; 30 cm)	[Watt]	background
IS/LEBT charge exchange		~0.1		none		
LEBT chopper	0.277			none		
LEBT beam recombination		< 0.005		none		
RFQ transmission		0.08		none		
MEBT chopper	0.042			none		
MEBT beam recombination		< 0.005		none		
Linac H-gas stripping			< 1.e-7/m		< 0.2 W/m	
Linac (warm)			< 2.5e-6/m	< 0.1	< 1 W/m	
Linac (SRF)			< 5.e-7/m	< 0.1	< 1 W/m	
HEBT collimators	1.e-3	1.e-5			2 kW	
HEBT H-magnetic stripping			< 1.e-8/m		< 0.02 W/m	
HEBT H-stripping			< 1.e-7/m		< 0.2 W/m	
Ring foil miss	0.02 - 0.1				40 - 200 kW	
Ring foil nuclear scattering		3.e-5			60 W	
Ring collimation section	2.e-3	1.4e-4		6.3 - 9.9	4 kW	100 - 1500
Ring extraction section			< 5.e-7/m	< 0.1	< 1 W/m	
Ring arc section			< 5.e-7/m	< 0.1	< 1 W/m	
Ring rf section			< 5.e-7/m	< 0.1	< 1 W/m	
RTBT collimation region		1.e-6			2 W	
RTBT (non-collimation)						
Target window		0.04			80 kW	
Goal	0.1		5.e-7/m			

Low-loss Design Philosophy



- Localize beam loss to shielded area
 - 2-stage collimation: HEBT, Ring, RTBT
 - 3-step beam-gap chopping/cleaning: LEBT, MEBT, Ring
- A low-loss design
 - Matching between linac structures; space charge effects
 - Resonance minimization; Magnet field compensation & correction
 - Proper lattice design with adequate aperture & acceptance
 - Injection painting; Injection & space-charge optimization
 - Impedance (extraction kicker) & instability control (e-p)
- Flexibility:
 - Adjustable energy (+/- 5%), Variable tunes (H 1 unit, V 3 units), flexible 3-D injection painting; adjustable collimation; foil interchange
- Accident prevention: Immune to front end, linac & kicker errors

Source of Uncontrolled Beam Loss



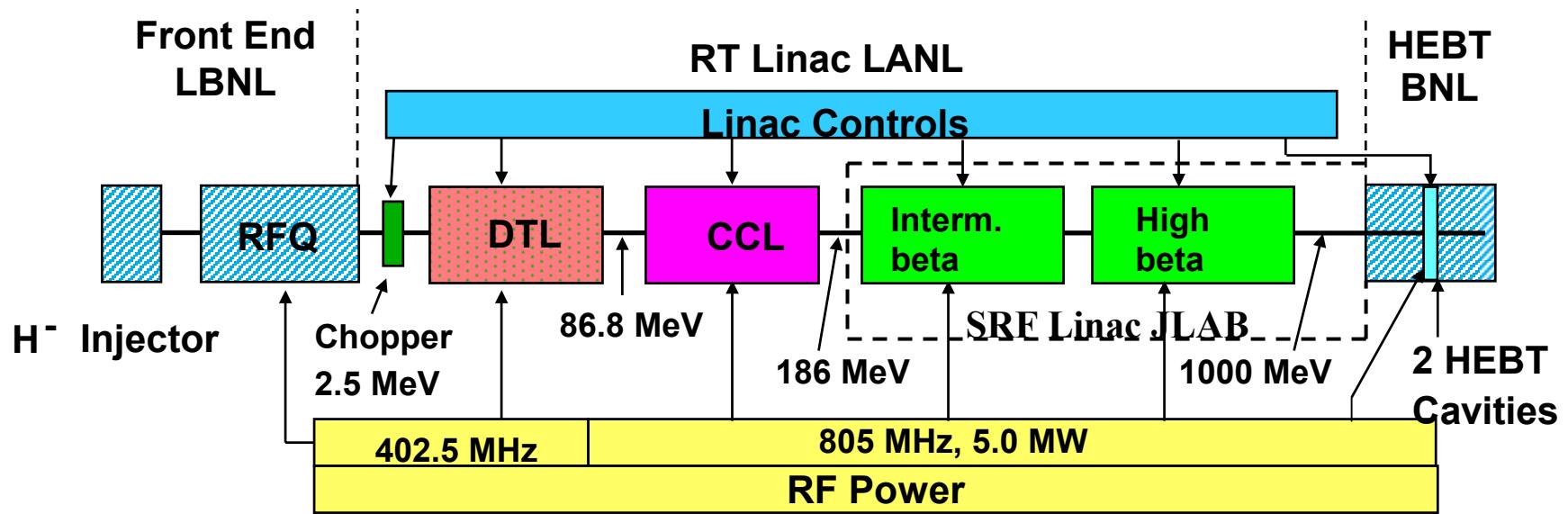
- Linac structure & lattice change: mismatches
- Space charge resonances: envelope, parametric halo, non-equipartitioning, tune shift & tune spread
- Physical aperture & momentum aperture limitation: dispersion, injection/extraction channel, chicane perturbation
- Ring injection loss: premature H⁻ and H⁰ stripping, foil hits
- Ring magnet errors: dipole-quad tracking; eddy-current & saturation, fringe field
- Instabilities: envelope, head-tail, microwave, coupled bunch, electron cloud
- Accidental loss: ion source and linac malfunction, extraction kicker failure

Linac Choice:

Superconducting RF Linac



- Adopting superconducting RF technology (186 – 1000 MeV)
- 2 types of cavity ($\beta=0.61$ and $\beta=0.81$) for economic savings & future energy upgrade
- One-cavity-per-klystron independent RF control of Lorentz detuning, microphonics, beam transients, injection offsets

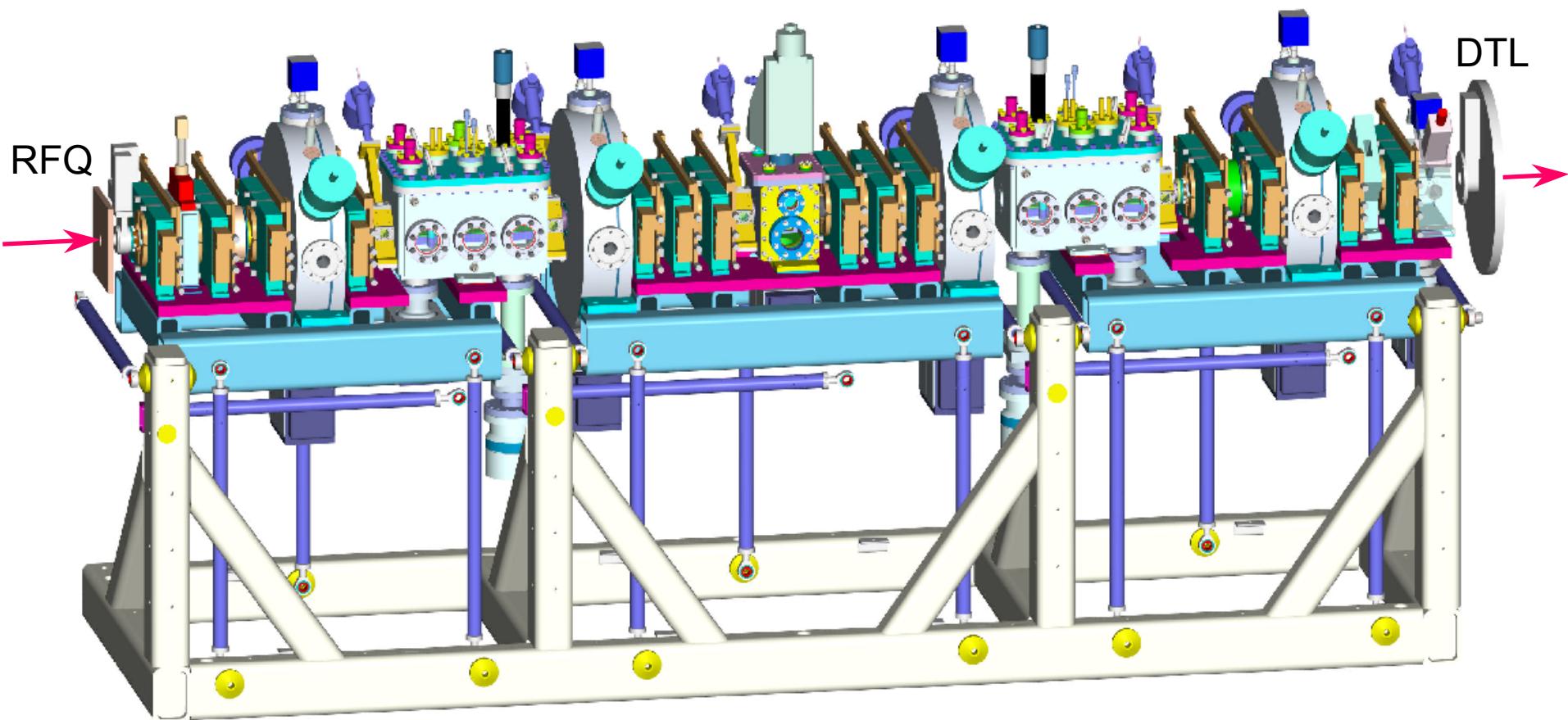


Linac Design Choices

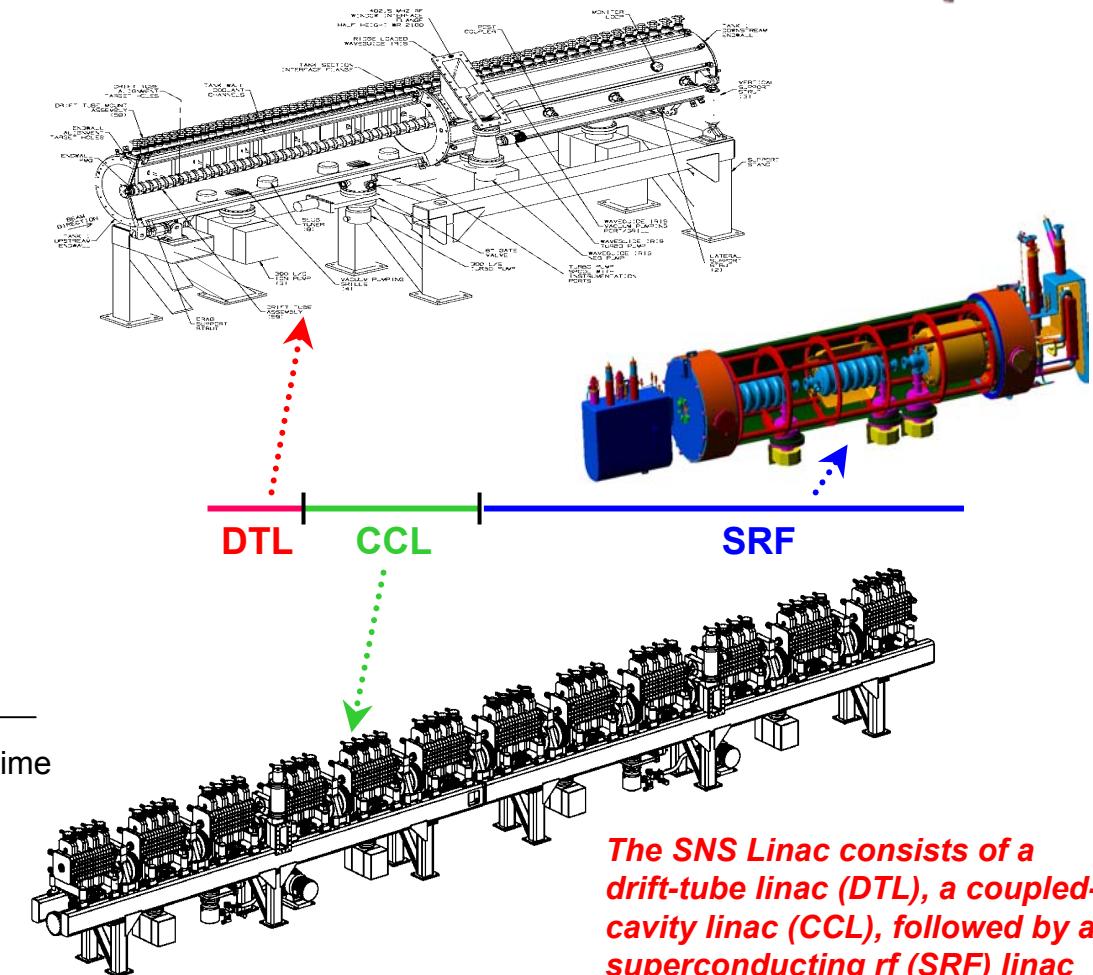
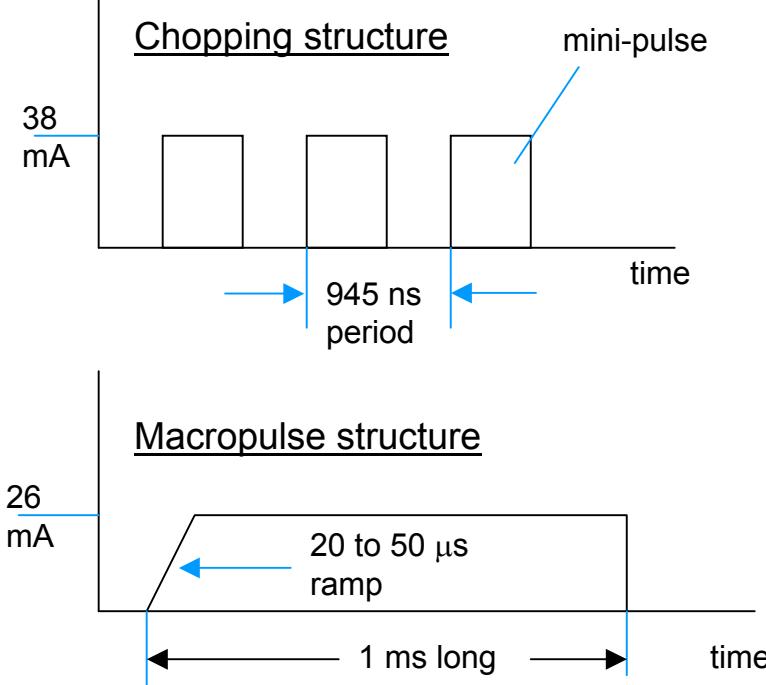


- Warm versus Super-conducting RF linac
 - SRF provides much higher gradient ($\sim 35 \text{ MV/m}$); provides saving & robust operation especially for higher duty cycle operation
- Linac RF control
 - SRF requires careful RF control on injection energy offset, Lorentz detuning, microphonics, beam loading/transient effects
 - One-klystron-per-cavity individual RF control for SNS linac
- Choice of SRF cavity beta type
 - Optimized two cavity beta type: flexible for gradient upgrade, but large phase slip requires detailed error sensitivity analysis
 - Constant gradient & continuous focusing: maximizing field strength but compromising equipartition law

MEBT Layout



Linac structure



Drift Tube Linac



Drift tube assemblies



Cu plating at GSI



Focusing magnets

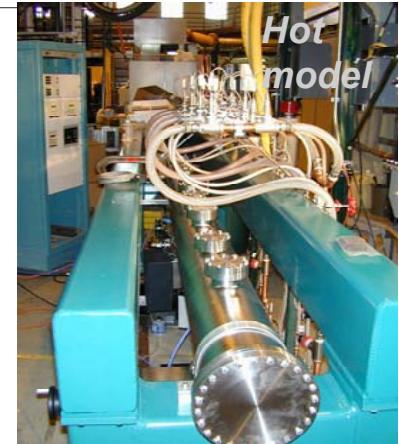
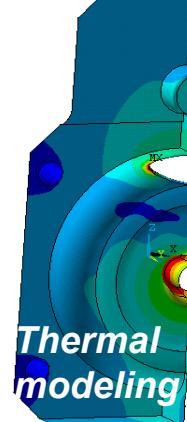
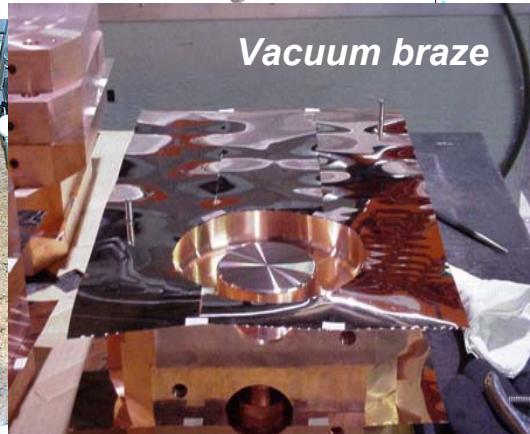
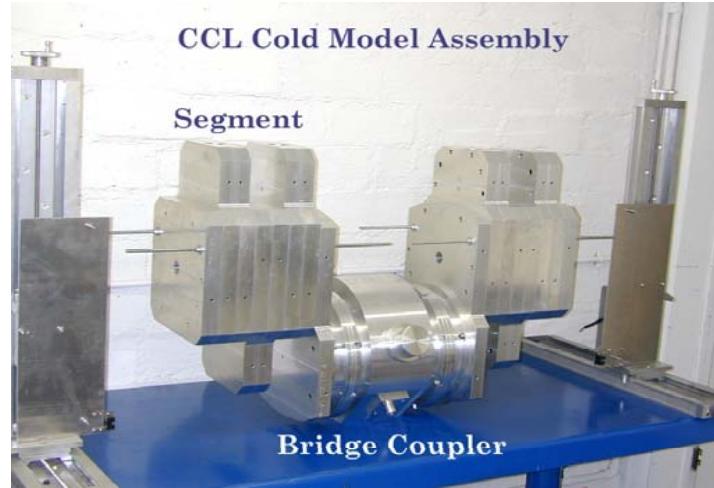
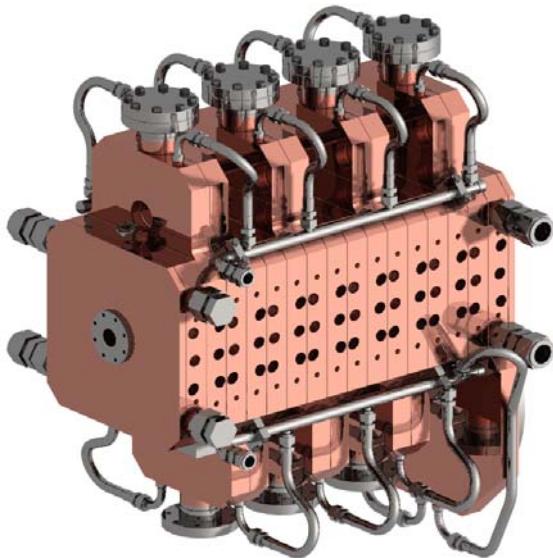


Tank forgings



Cold model

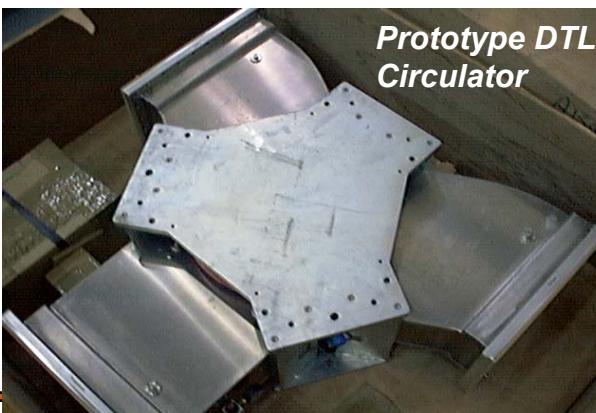
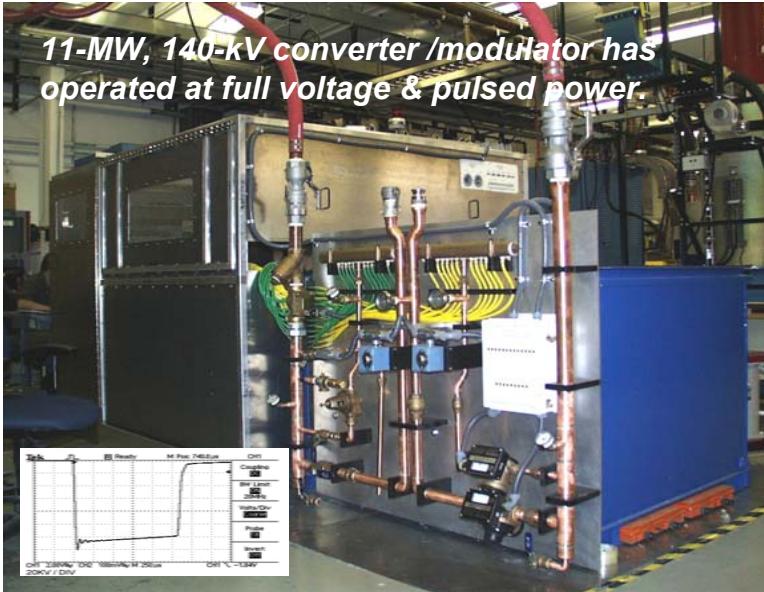
Coupled-Cavity Linac



Linac RF System



First 402.5-MHz klystron for the SNS DTL.
All SNS klystrons are now under contract.



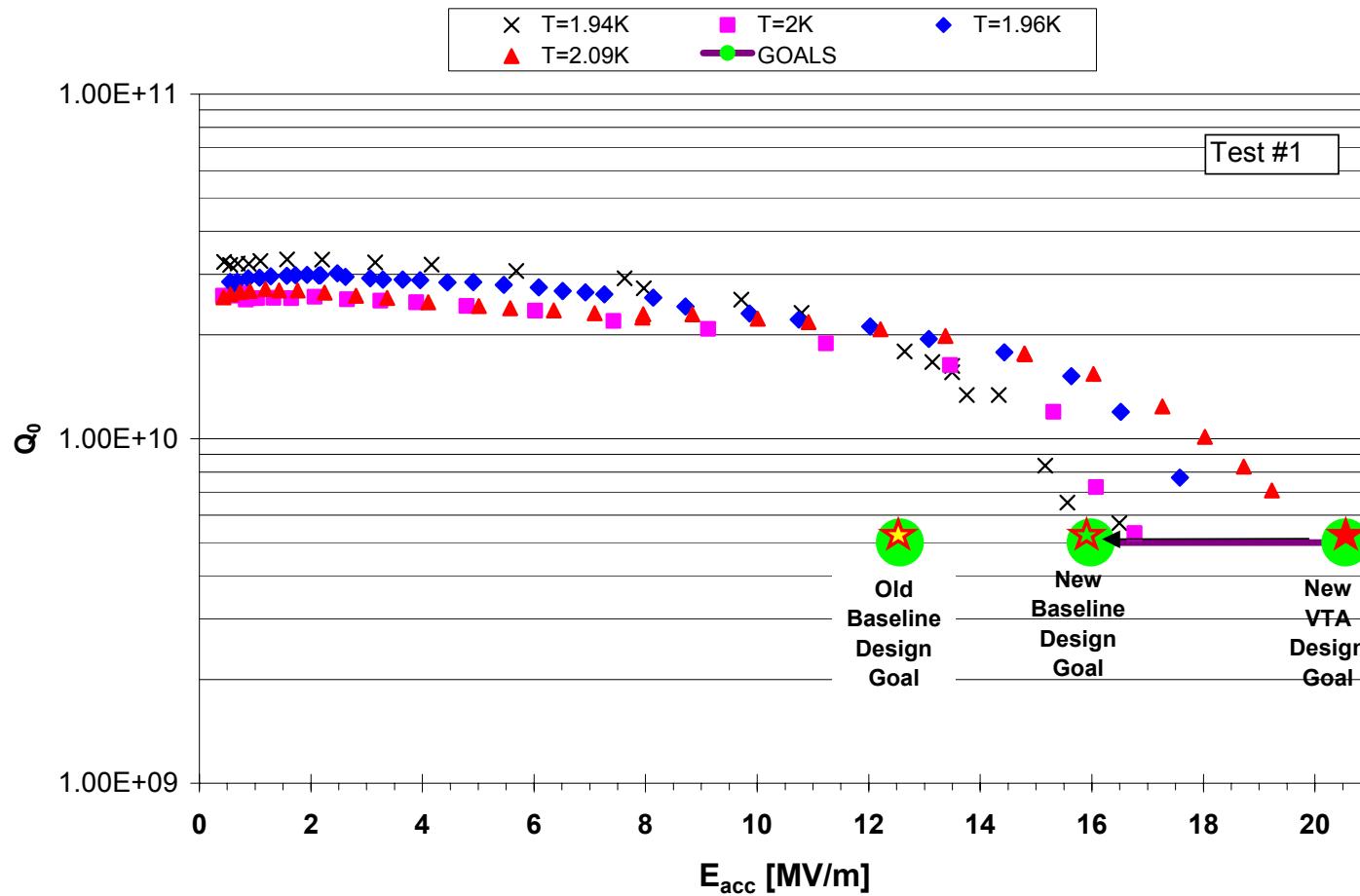
All klystron transmitters
are under contract

Beta 0.81 Cavity #5 Test Results



6 cells $\beta=0.81$ cavity 6SNS81-1 stiffening ring at 80mm

Q_0 vs. E_{acc}



Linac challenges



- Key challenge
 - Effective emittance growth & ring injection activation
 - Compared with other facilities (e.g. 5 –8 times growth at LANSCE), identified transverse jitter as main issue; easier for 402.5 MHz DTL
- Resonance, non-equipartition & halo
 - Parametric resonance: depending on level of mismatch (extensive study with APT, and Ryne, Qiang's work ...)
 - Space-charge coupling resonance: resonance possible; impact under investigation (I. Hofmann's work ...)

Linac emittance comparison



Machine	Energy [MeV]	Peak current (in) [mA]	Peak current (out) [mA]	Emittance (in) [p mm mr]	Emittance growth (times)	Species	Comments
IUCF	7	1	1	0.3	3.3	P	RFQ/PMQ
IHEP©	35	250	40	3	2	P	
KEK	40	25	18	0.4	3	P	
DESY	50	60	18	0.6	3.3	H-	RFQ
CERN	50	300	150	0.8	6.3	H-	RFQ
RAL	70	35	25			H-	RFQ
IHEP®	103	300	100	0.2	10	P	
BNL	200	100	40	0.4	5	H-	RFQ
FANL	400	100	50	0.1	15	H-	
INR	423	250	20	0.5	3	P	
LAMPF	800	20	16	0.09	5 -- 8	P	
SNS	1000	56	52	0.2	2.5	H-	RFQ/PMQ

- Key figure of merit for SNS linac performance:
 - Emittance preservation & pulse-to-pulse transverse jitter control
 - Energy spread preservation & pulse-to-pulse energy jitter control
 - Consider measurement conditions & factors (vibration sensitivity ...)
 - How well does measurement agrees with simulation?

Linac beam quality demands



- Output energy within +/- 5% window
 - Key challenge: control transverse emittance and jitter
 - Effective beam size growth & ring injection activation (< a factor of 2)
 - Compared with other facilities (e.g. 5 –8 times growth at LANSCE), identified transverse jitter as main issue; easier for 402.5 MHz DTL
 - New halo findings based on non-water-bag measured distributions
 - Control momentum spread and jitter
 - Facilitate longitudinal painting with a narrow paint brush
 - Need to control total energy deviation within +/- 0.3% (3 MeV)
 - Phase error an added complication
 - Reduce uncontrolled beam loss across linac
 - About 1 W/m and lower
-

SC RF linac comparison

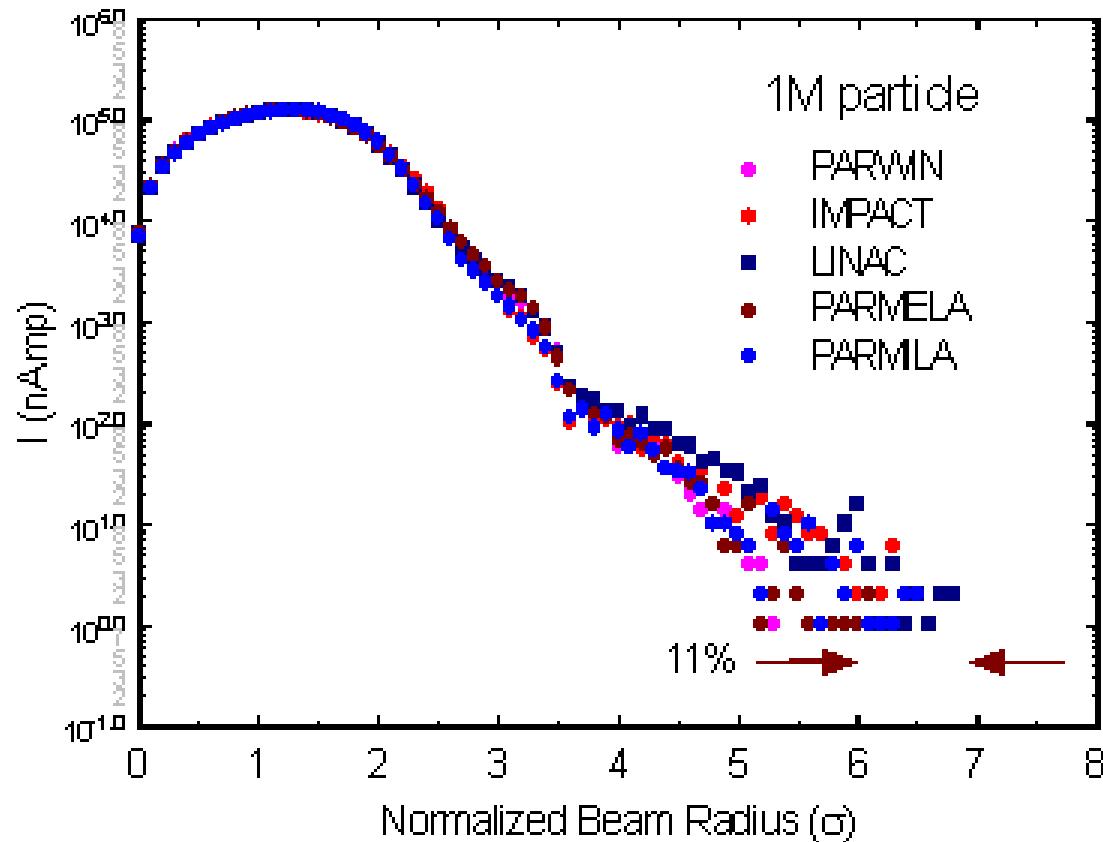


	SNS	JJP	ESS	SPL	APT	TRASCOMASH
Institute	DOE 6 labs.	JAERI/KEK	EU	CERN	LANL	INFN/CEA
frequency [MHz]	805	972	700	352.2	700	704.4
Eergy [MeV]	185 -- 1250	400 -- 600	70--1334	120 - 2200	212 -- 1030	85--2000
Beam Power [MW]	> 2	0.75	5	4	103	4
Rep. Rate [Hz]/Pulse length [ms]	60/1	60/0.75	50/1	75/2.2	CW	CW
Length [m]	237	110	~300	691	514	506
Real estate acc. Gradient [MV/m]	4.5	1.82	~4.3	3	1.6	3.8
Number of β	2	2	4	4	2	3
Cavity β (geometrical)	0.61, 0.81	0.73, 0.77	0.5, 0.6, 0.75, 0.9	0.52, 0.7, 0.8, 1	0.64, 0.82	0.5, 0.68, 0.86
peak (avg.) current [mA]	52 (2)	50	107 (3.75)	67 (11)	100 (100)	20 (20)
Max. acc. grad. (interial cell) [MV/m]	10.5, 12.8	9.9, 10.5	~10	3.5, 5, 9, 7.5	6.1, 7.1	8.5, 10.2, 12.3
peak surface Epeak [MV/m]	27.5	30.2, 29.9	n/a	?	19.0, 19.7	30.4, 26.5, 29.2
peak surface Hpeak [mT]	57, 59	52.5	n/a	?	42.3, 44.5	50
Inter-cell coupling (%)	1.6	2.9, 2.6	n/a	?	?	1.34, 1.1, 1.28
number of cavities	117 (33+59+25)		~168	230	242	234
lattice	warm doublet	warm doublet	warm doublet	warm doublet	warm doublet	warm doublet
longitudinal phase law	const grad/cont. F	equal phase slip			constant power	
transverse phase law	constant gradient	equipartitioning			const. phase adv	
rf control	invididual	vector sum		invid/vector sum	vector sum	vector sum
cavity / klystron	1	2	?	?	(2,3), 2	2,2,4
cell / cavity	6	7	5	4,4,5,4	5	5,5,6
cavity / cryomodule	3, 4	2	2	3,4,4,4	(2,3), 4	2,2,4
power coupler/cavity	1	1	1 or 2	1	2	1
Applications	Neutron scattering	transmutation	Neutron scattering	neutrino factory	tritium production	transmutaion

Codes benchmarking on SNS linac

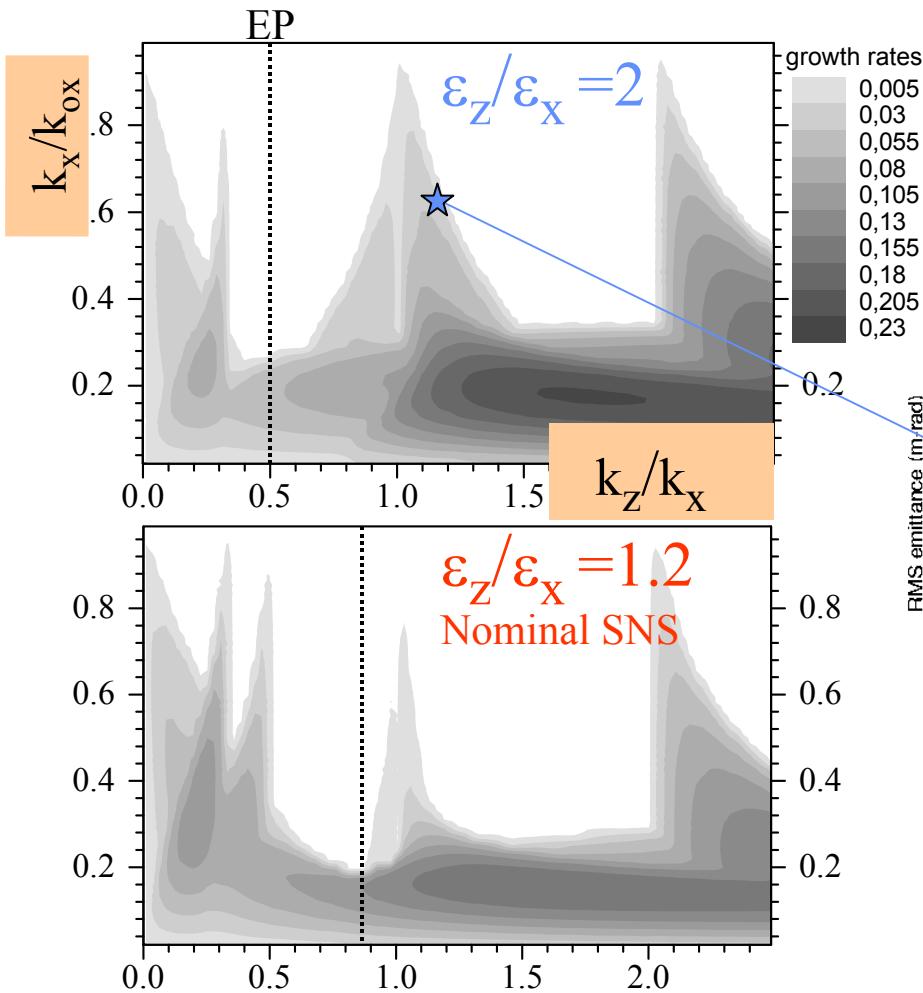


Particle Distribution at 7.5 MeV
5 Codes

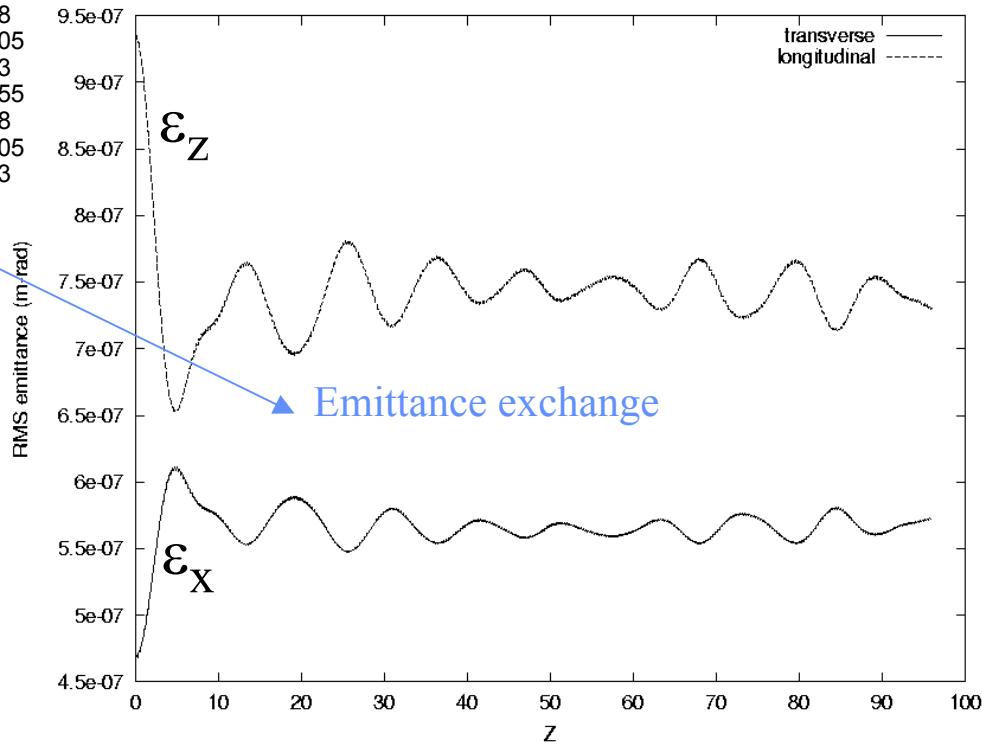


Linac space-charge resonances

main candidate is avoided in SNS for nominal emittance ratio 1.2



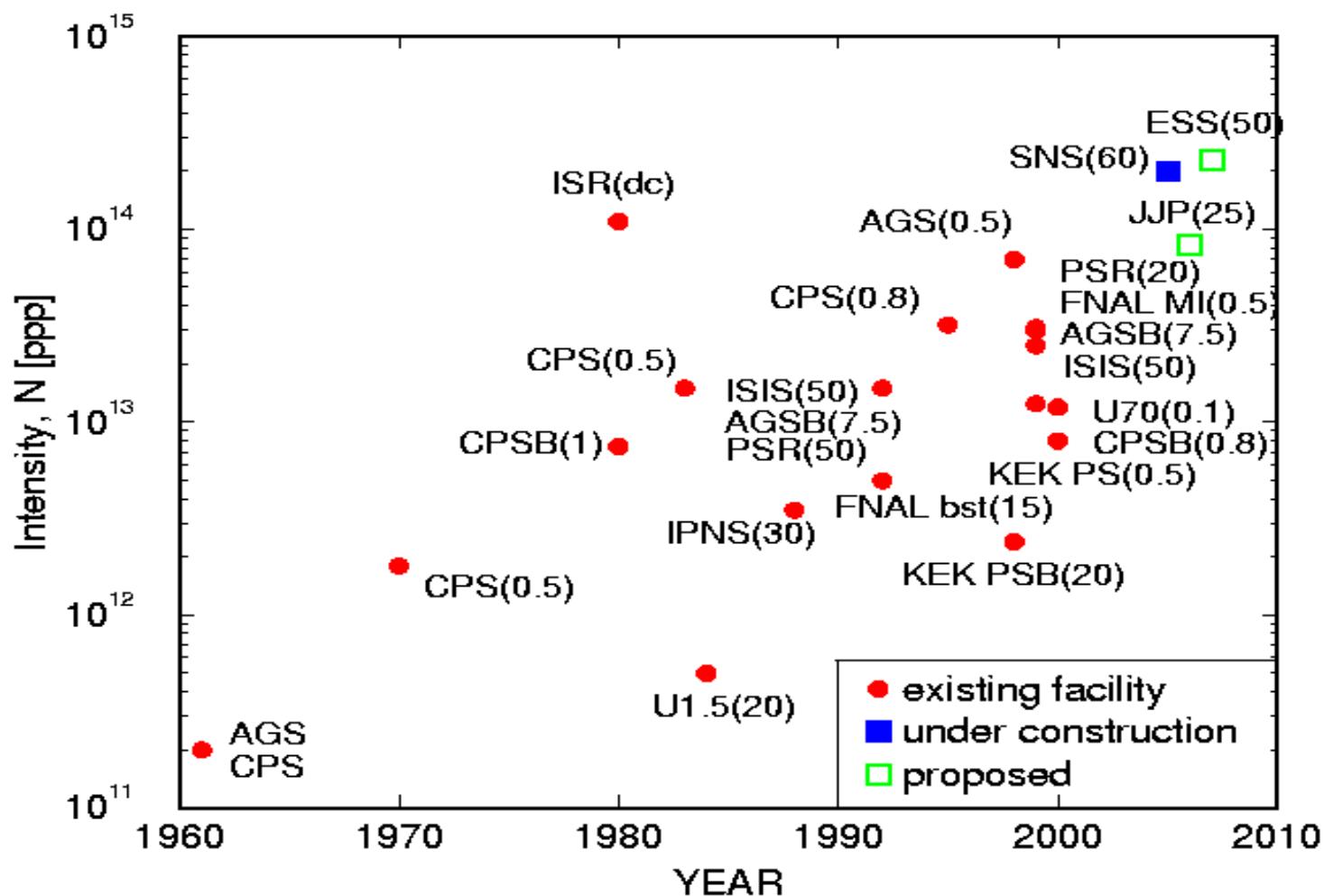
I. Hofmann et al TPPH033



IMPACT code (Qiang/Ryne, LANL) in constant focusing

Analytical Resonance Chart

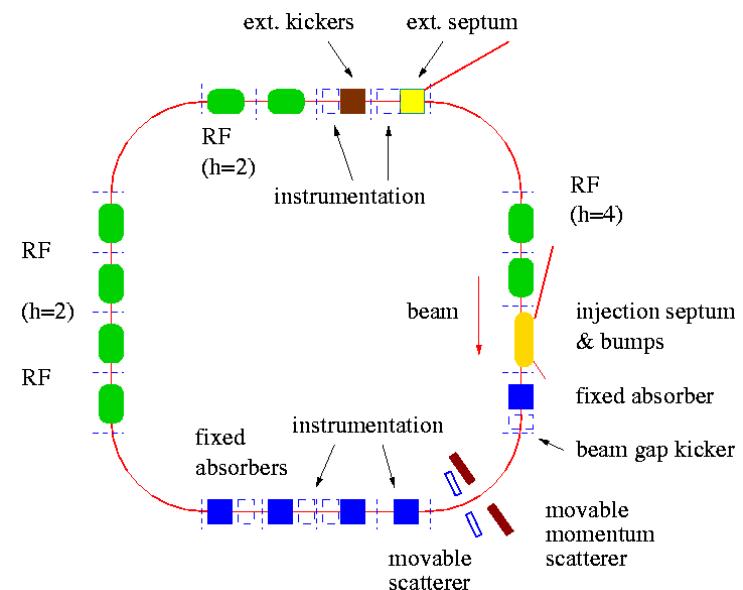
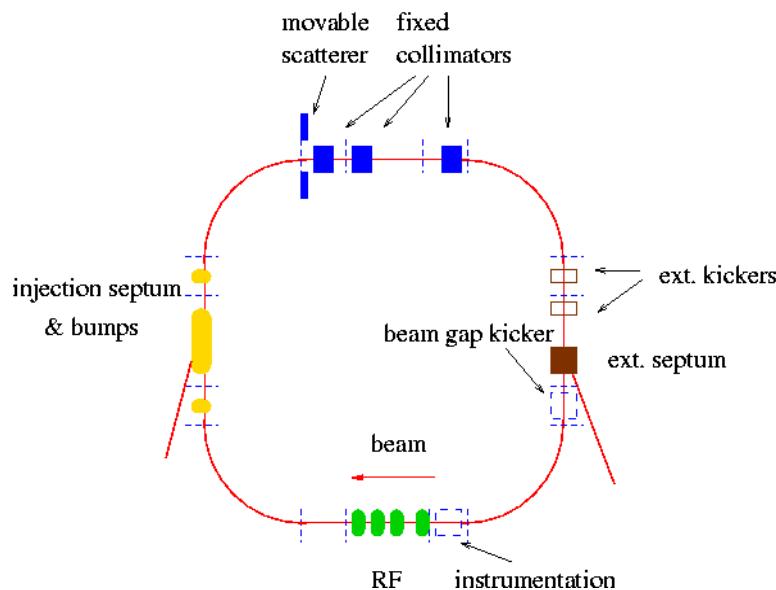
Ring beam intensity evolution



Ring Choice: *Accumulator vs. Synchrotron (RCS)*



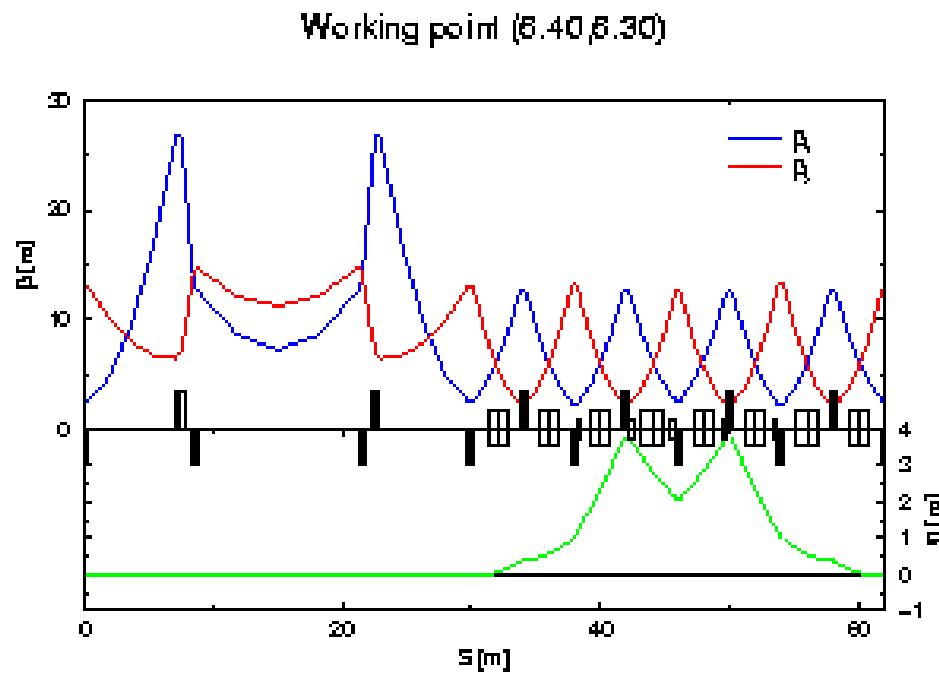
- Chosen full energy linac & accumulator ring
 - Simpler ring design, no magnet ramping, better field quality
 - Shorter ring storage time, less instability, lower beam loss



Ring Lattice: *FODO arcs & doublet straights*



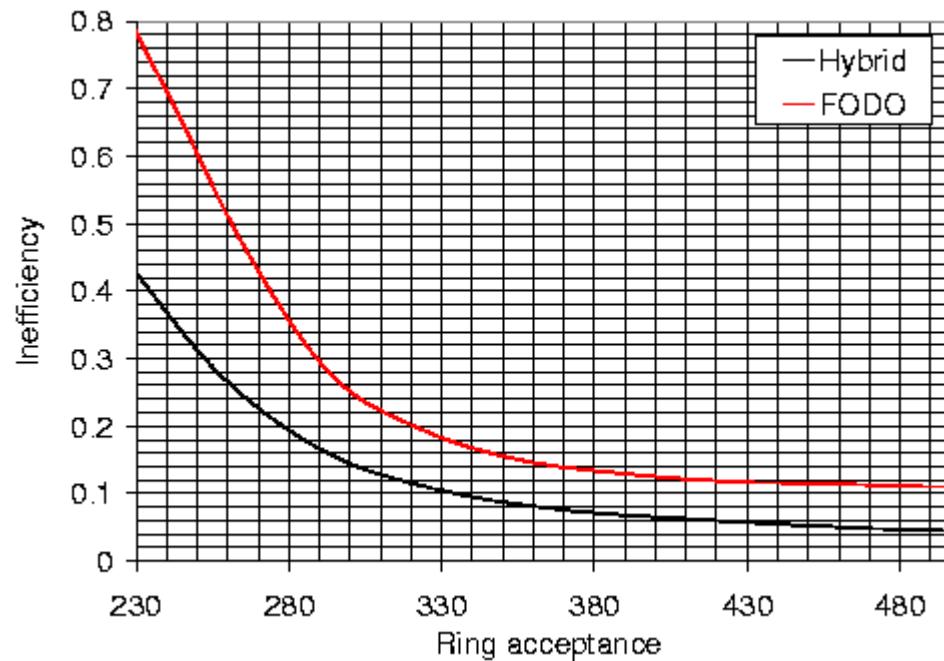
- Matched, hybrid lattice
 - FODO arc:
easy-to-implement correction system, moderate magnet strength
 - Doublet straight:
long, uninterrupted straight
 - » Improved collimation efficiency
 - » Robust injection
- Zero-dispersion injection
 - Independent painting in the transverse & longitudinal directions



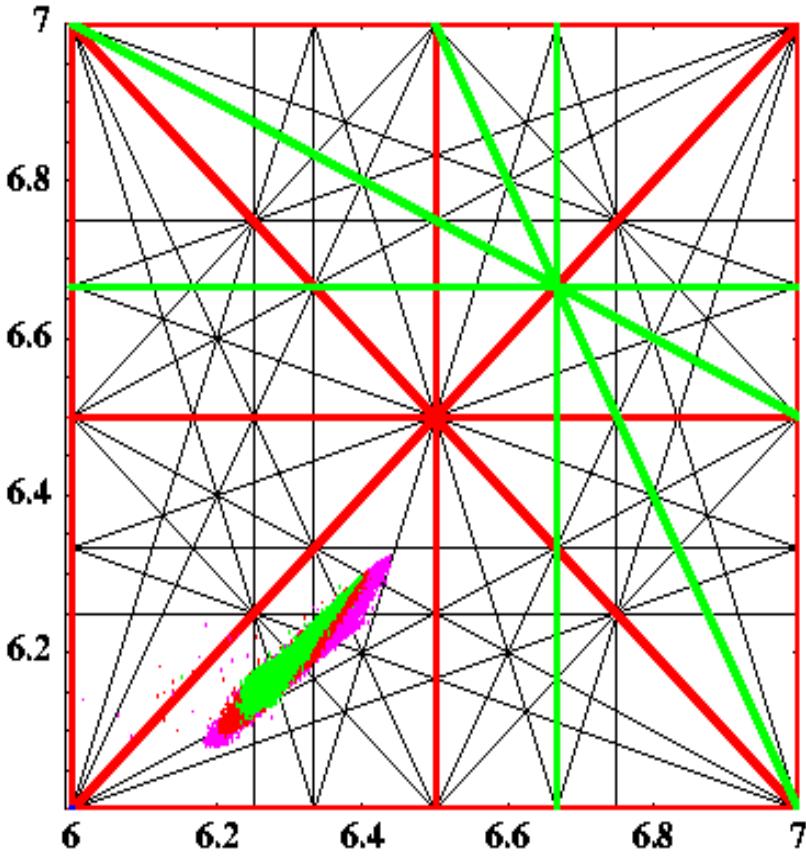
Lattice for transverse collimation



- Dispersion-free region for betatron collimation
- Allow flexible arrangement at optimum phase advance
- Usually prefer doublet/triplet lattice with long drift space



Ring tune spread

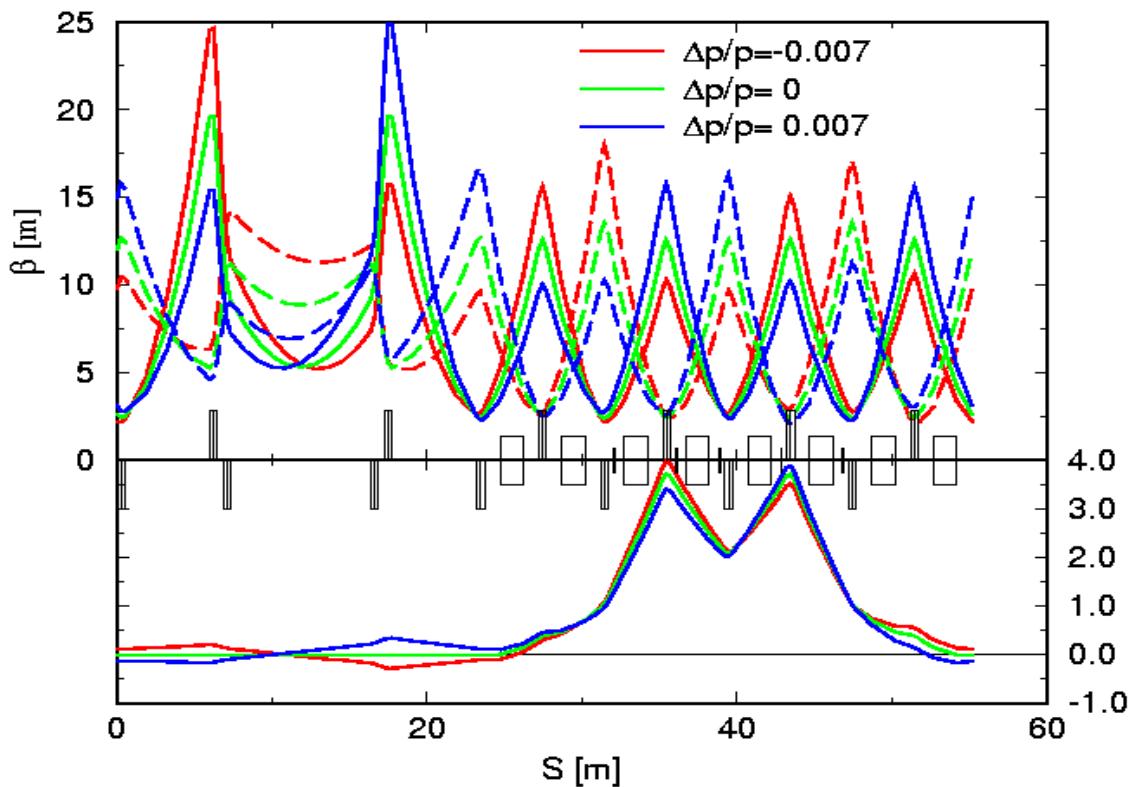


- 2 MW beam at 1 GeV
 - Space charge tune spread about 0.2 (green)
 - Chromatic tune spread must be controlled by sextupoles (red: beam core $\Delta p/p = +/- 0.6\%$; pink: partial halo $\Delta p/p = +/- 1.0\%$)
- Magnet non-linearity not shown
 - At 10^{-4} error level, dominated by space charge growth/diffusion
 - At 10^{-3} error level, dominated by dynamic aperture
 - Misalignment a strong factor (dilation factor ~ 20)

Chromaticity Control

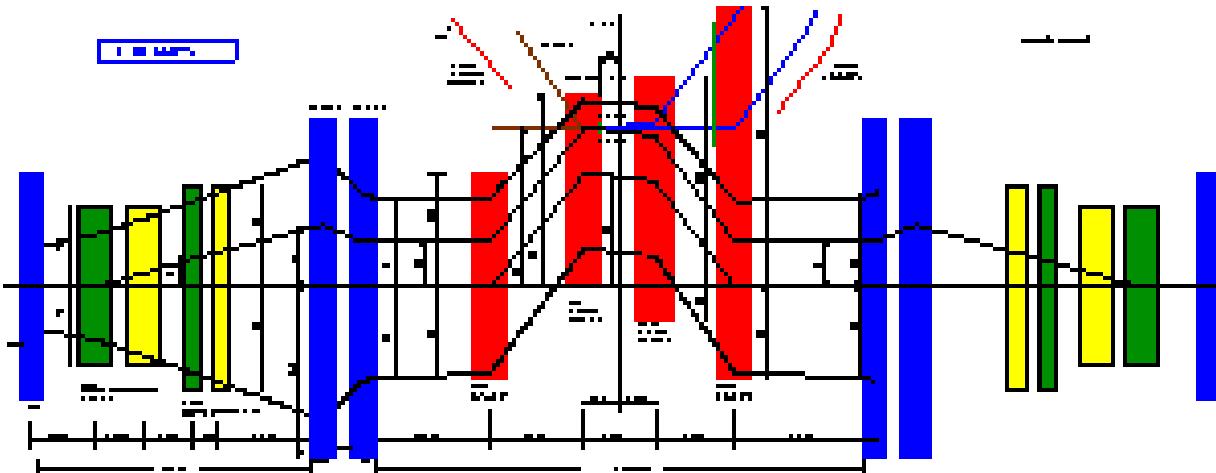


Limitation of a 2-family sext. system



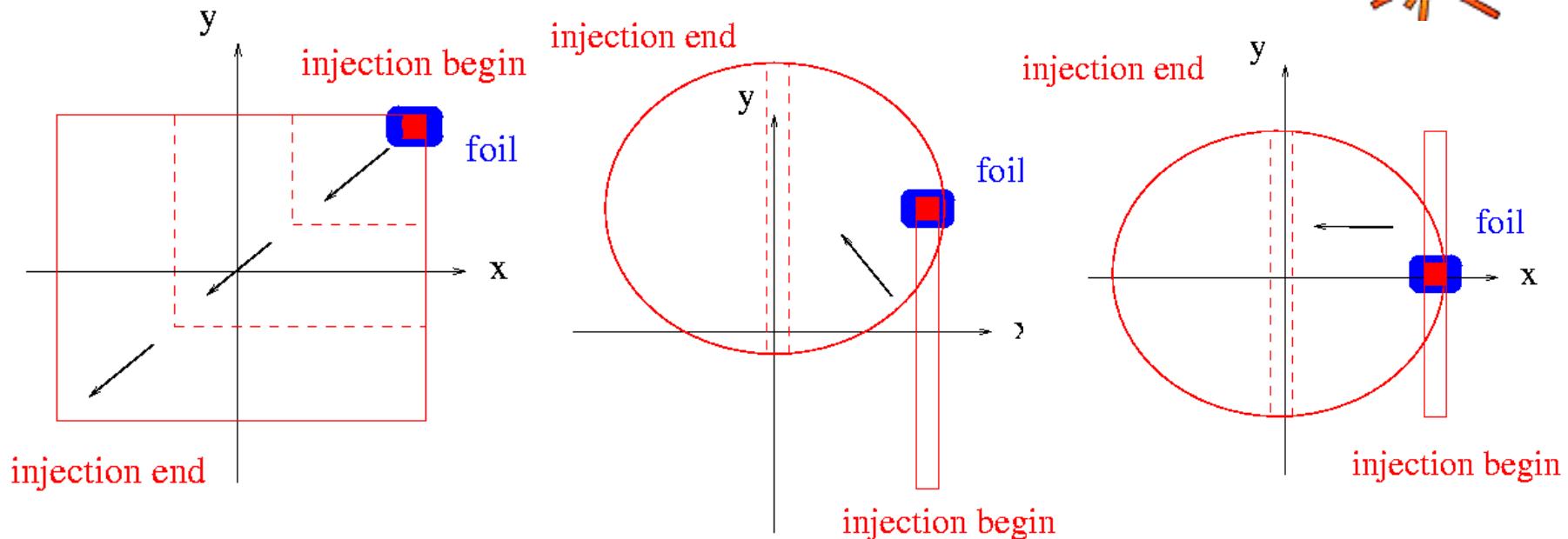
- Not used at ISIS; helpful at PSR
- Needed for increasing momentum spread
- Preserve lattice symmetry:
 - Avoid resonance
- Multi-family (4) sextupole:
 - Preserve dynamic aperture
 - Full chromaticity control

SNS injection (zero-dispersion)



- Independent H, V, L control
- Circular & square profile both attainable
- Energy corrector & spreader in HEBT
- Tolerable to momentum errors
- Small residual $\Delta\beta/\beta$ & dispersion

Transverse painting schematic



Correlated
bumps

Anti-Correlated
bumps

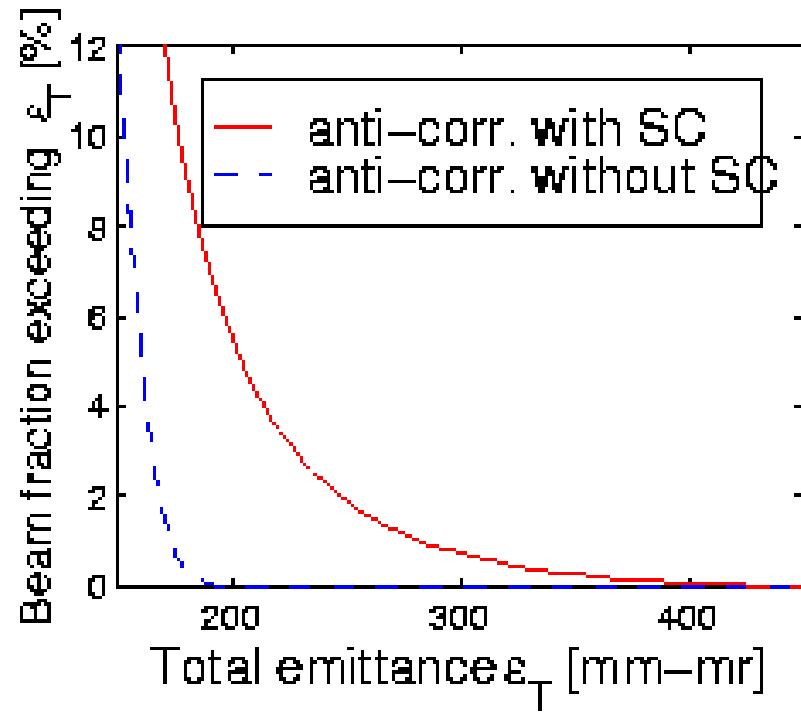
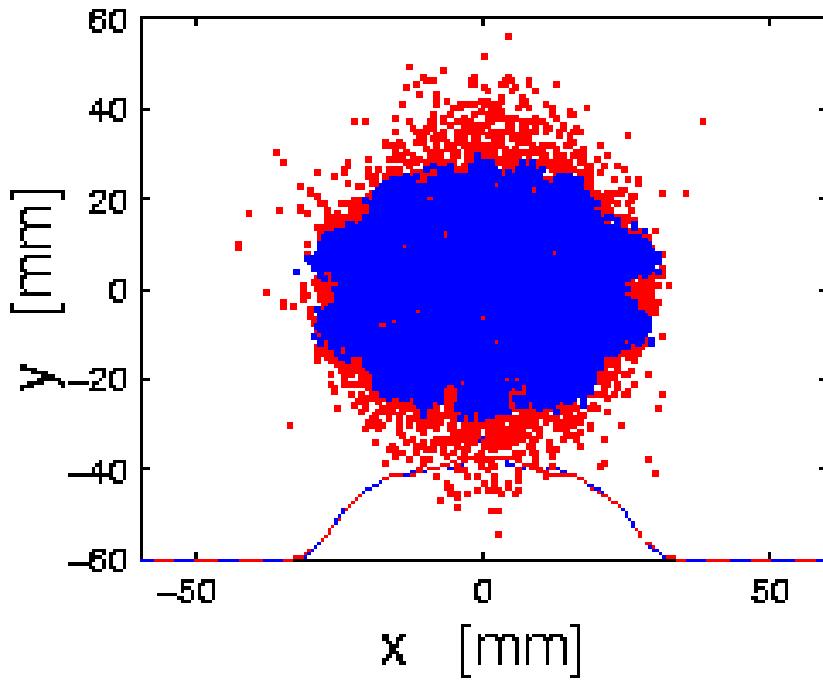
Paint (H)/
steer (V)

Painting scheme comparison



Scheme	Advantage	Disadvantage
Correlated	Paint over halo (square beam profile)	Singular density Coupling emittance growth
Anti-correlated	Ideal uniform distribution Immune to coupling (circular beam profile)	Halo growth due to space charge
Coupled (correlated)	Paint over halo (diamond beam profile)	Extra 50% aperture Extra acceptance needed
Paint (H) / steer (V)	Similar to anti-corr. Paint Less fast kickers	Foil support difficult suscep. to operational error
Paint (V) / steer (H)	Similar to anti-corr. Paint Less fast kickers	Vertical injection suscep. to operational error
Oscillating bump	Uniform distribution Paint over halo	Fast power supply switch Extra 50% aperture (H & V)

Ring space charge & halo

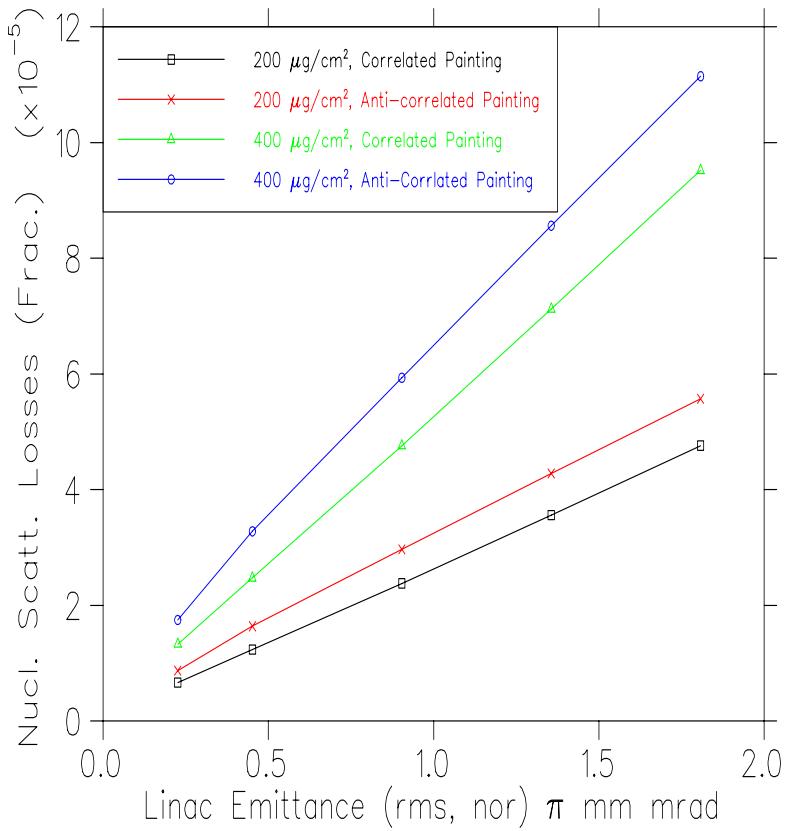


- Parametric core-particle halo: often not important for ring
- Strongly coupled with magnet nonlinearity
- Cure: tune selection, resonance corr., bunching factor enhancement

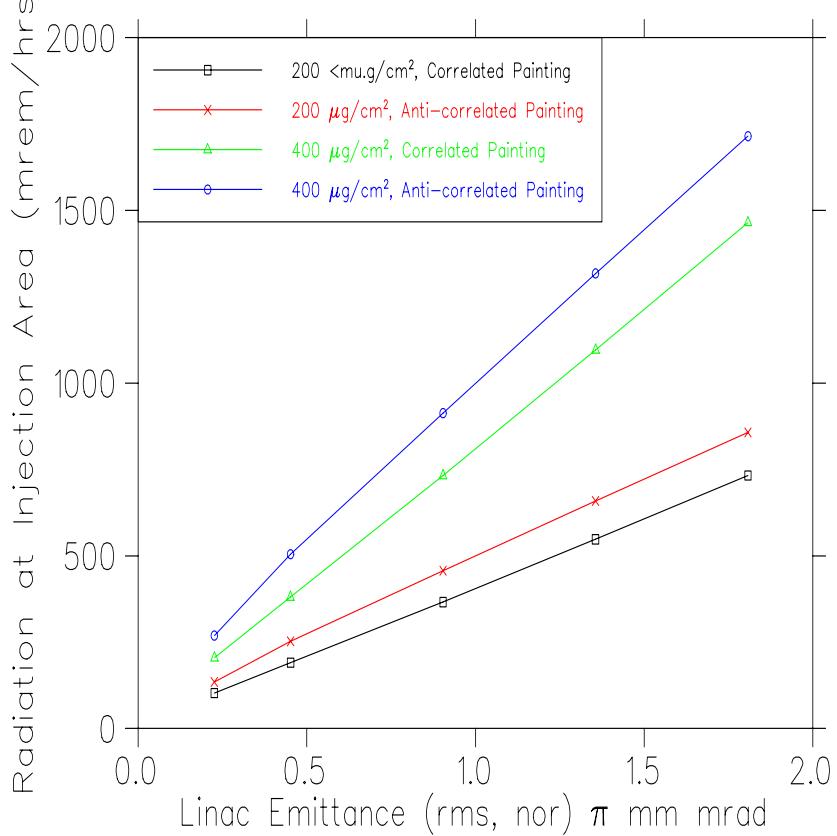
Radiation due to nuclear scattering



Particle Loss (Fraction)



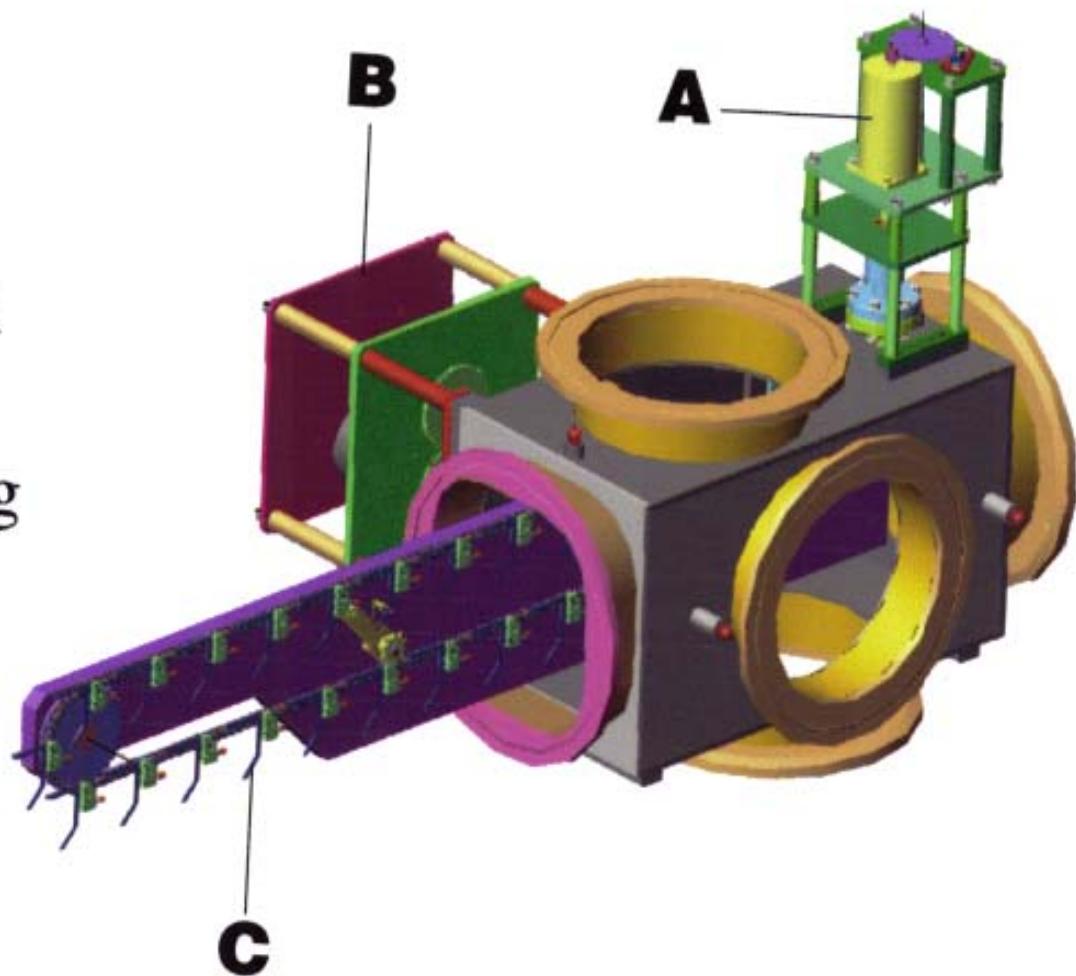
Radiation at Injection Area



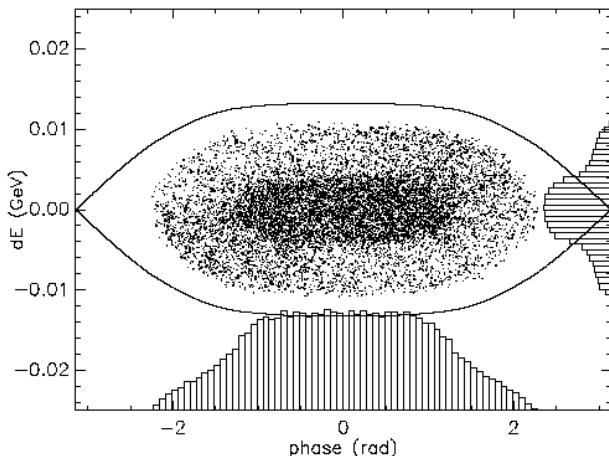
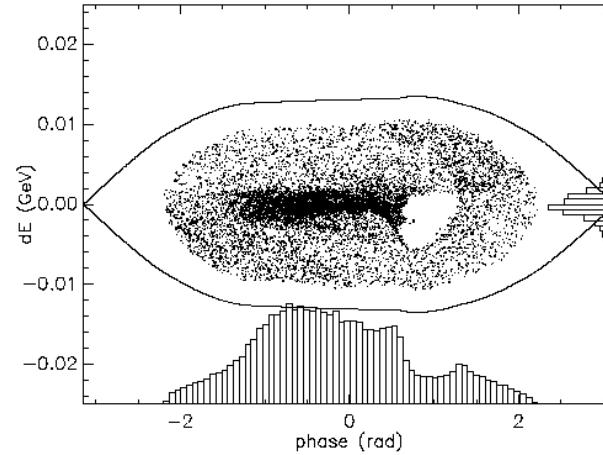
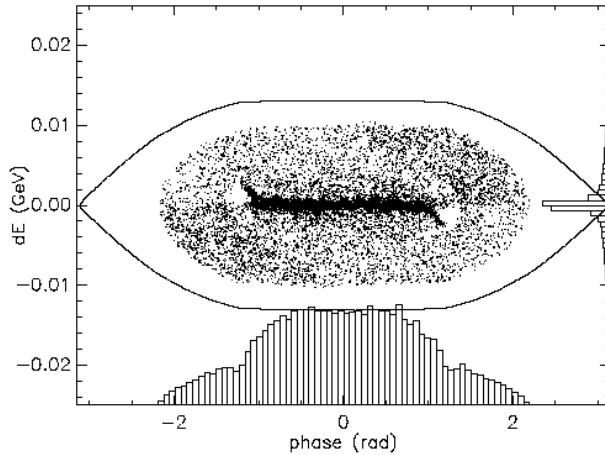
SNS injection foil device



- A.** Foil Insertion Control
- B.** Foil Changing Control
- C.** Foil Holders



Longitudinal Requirements

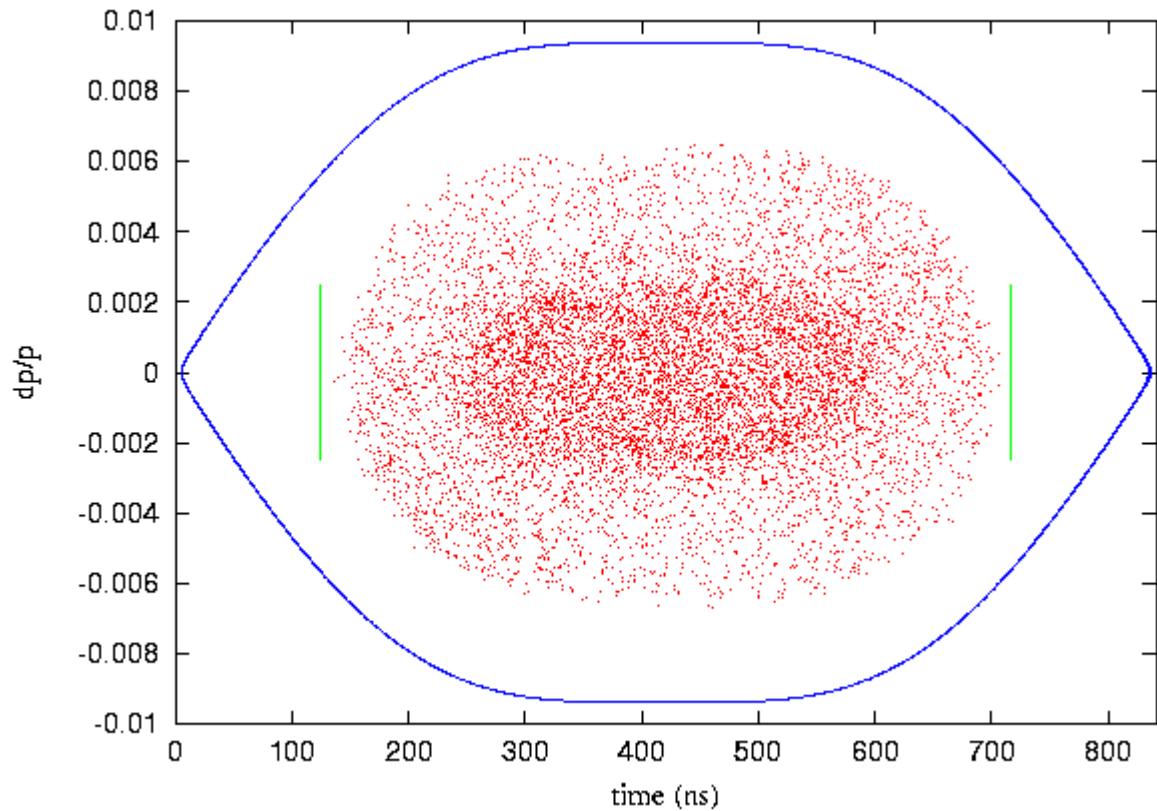


- Facilitate longitudinal painting (instability, beam-in-gap cleaning, loss)
 - No spreader, on energy
 - No spreader, off energy
 - With corrector & spreader

Beam-gap cleaning



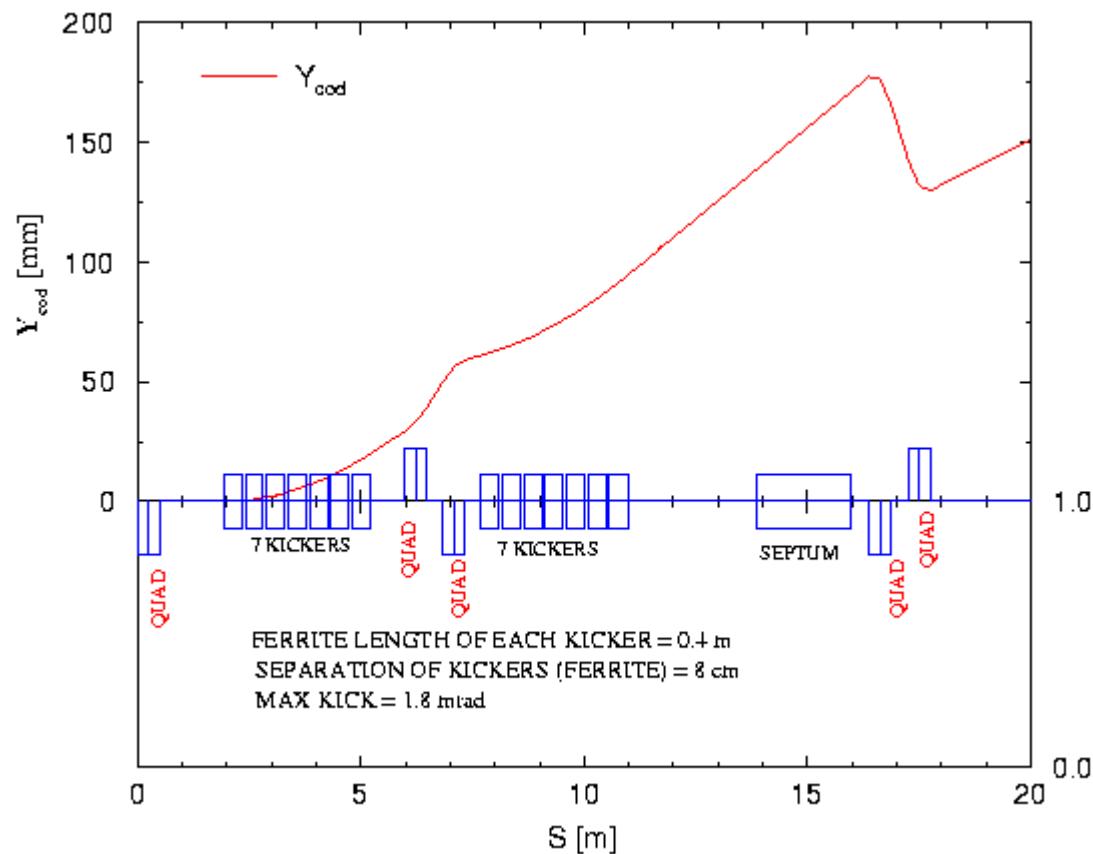
- Strip-line kicker at betatron frequency to kick-out particles in tens of turns
- Gated at beam gap, with rise/fall time much shorter than gap length
- Can be used for momentum cleaning if aperture is adequate
- Tune spread may cause complications



Extraction layout



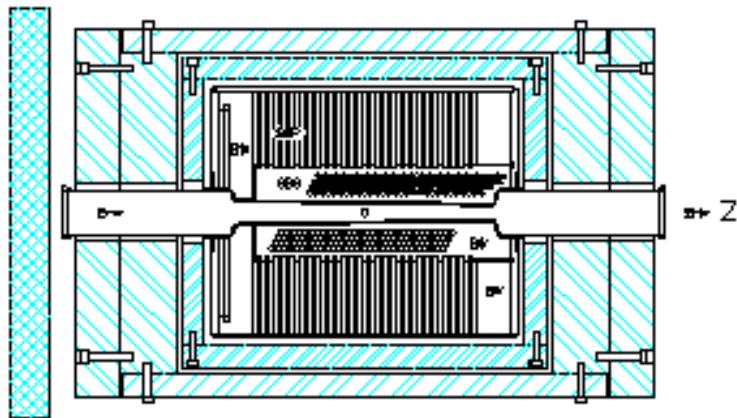
- Multiple (14) kickers vertically deflect beam
- Horizontal bending beam away with a Lambertson dipole
- Single-turn, no pre-bumps
- Clean extraction with 1 kicker failure
- Beam spot position on target unchanged upon kicker failure



Two-stage Collimation & Collection



COLLIMATOR
STAINLESS STL SHELL & BORE TUBE
SSP = STAINLESS STL PLATES
SSS = STAINLESS STL SHOT
BW = BORATED WATER



REMOVEABLE
LEAD SHIELD
17.5 CM THK

IRON INNER & OUTER SHIELDS
COLLIMATOR SECURED INSIDE INNER SHIELD
INNER SHIELD HEIGHT ADJUSTABLE

SCHEMATIC OF COLLIMATOR COMPONENTS
HORIZONTAL SECTION

- Achieving $> 90\%$ efficiency by enhancing the impact parameter
- Primary adjustable, thin platinum scrapers (4)
- Secondary fixed, self-shielding collimator
- 2-stage collimation bench-marked (within 20% error) on SPS
- Lower energy test underway (SNS & Protvino U70)

Ring Beam-gap Cleaning



- Three stage: LEBT (50 ns); MEBT (10 ns); Ring (10 ns), momentum cleaning
- Gated excitation at betatron frequency
- Used on NSLS & ESRF light source to kill stray bunches (1993)
- Tested at HERA
- Essential momentum cleaning method for accumulators

SNS Dipole Magnet



Magnet, Fringe Field, Compensation



- Dominant error: eddy current (ramp matching), saturation; limit peak field (e.g. 1 T) and ramp rate (e.g. 30 T/s) (e.g. 5%)
- Eased by programmable ramp (IGBT switch etc)
- Dominant field components: allowed multipoles (e.g. 2%); correctable by magnet pole shaping
- Fringe field:
- Important for large acceptance, moderate ring circumference (e.g. 0.2%)
- Order of magnitude: **(emittance) / (magnet length)**
- (or $(\varepsilon/L)\beta'$ when $\beta' \gg 1$, e.g. collider IR)
- Correctible with octupole correctors

Ring Correction Packages



Effects	Correctors	Quantity	Powering
Closed orbit distortion	Dipole	52	Individual
Quadrupole perturbation	TRIM Quadrupole strings	52	16(+8) families
Tune correction during accumulation	"Pulsed" Quadrupoles	8	4 families
Coupling	Skew Quadrupoles	16 (+26)	Individual
Chromaticity correction	High-Field Sextupoles	20	4 families
Normal sextupole resonances	Normal Sextupoles	8	Individual
Skew sextupole resonances	Skew Sextupoles	16	8 families
Tune-shift with amplitude + resonances	Octupoles	8 (+4)	Individual

- Under study

Ring simulation codes



	UAL	ORBIT	FTPOT	MAD 8	MARYLIE 3.0	ACCSIM	SIMPSONS
Interface	PERL API	SuperCode	FTPOT	MAD	MARYLIE	ACCSIM	SIMPSONS
MAD elements	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Errors	Yes	No	Yes	Yes	No	No	Yes
Tracking	Thin lenses	Matrices + nodes	Thin lenses	Lie algebra	Lie algebra	Matrices + nodes	Thin lenses
Mapping	Any order	Second order	Second order	Third order	Third order	Linear order	No
Painting	Yes	Yes	No	No	No	Yes	Yes
3D Fringe Field	Yes (Maps)	No	No	No	Yes	No	No
Space Charge	2.5D	2.5D	No	No	No	2.5D	2D and 3D
Analysis (Twiss ...)	Yes	No	Yes	Yes	Yes	No	No
Optimization (Lattice ...)	No	No	No	Yes	Yes	No	No
Correction (Orbit ...)	Yes	No	Yes	Yes	Some	No	No
Impedance	in progress	Yes	No	No	No	No	No
Collimator	in progress	Yes	No	No	No	Yes	No
Integration of lattices	Yes	No	No	No	No	No	No

Ring impedance budget (< 10 MHz)



	Z_L/n [Ohm]	Z_T [k Ohm/m]
Space charge	-j 196	-j 7,720
Extraction kicker, 50Ω termination	$35 + j 42$	$21 n + j 200$
Extraction kicker, open termination	$35 + j 42$	$9 n + j 200$
RF cavity	Active feedback on ω_{rf}	j 10
Injection foil assembly	Under study	Under study
Resistive wall	(j + 1) 0.7, at ω_0	(j+1) 6.2, at ω_0
Broadband		
BPM	j 4.0	j 58
Bellows	j 1.5	j 14
Steps	j 1.6	j 14
Ports	j 0.5	j 4.4
Valves	j 0.15	j 1.4
Collimator	j 0.22	j 2.0
Total BB	j 8.0	j 94.0

Measures on electron-cloud



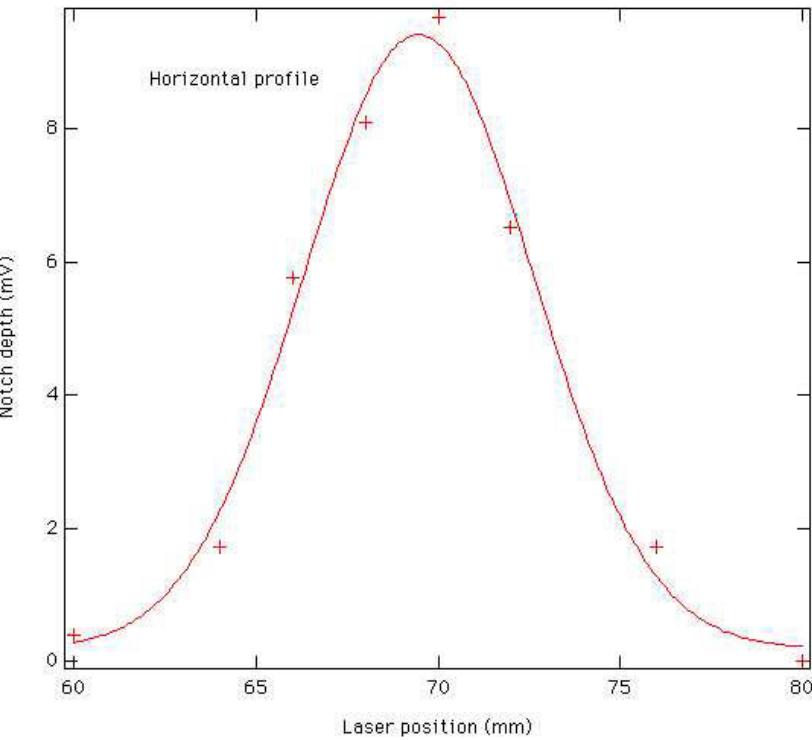
- Ring design incorporated all known e-p mitigation features
 - Implementations to minimize electron production
 - » Tapered magnets for electron collection near injection foil
 - » TiN coated vacuum chamber to reduce multipacting
 - » Striped coating of extraction kicker ferrite (TiN)
 - » Beam-in-gap kicker to keep a clean beam gap (10^{-4})
 - » Relatively high vacuum (5×10^{-9} Torr)
 - » ports screening, step tapering
 - » Install electron detectors around the ring; possibly wind solenoids?
 - Machine design to enhance damping
 - » High RF voltage to provide momentum acceptance:
40 up to 60 kV (h=1) + 20 kV (h=2); momentum painting
 - » Planned lattice sextupole families for chromatic adjustments
 - » Reserve space for possible wide band damper system

AP requirements on diagnostics



Device	Location	Intensity [ppp]	Pulse length [μ sec]	Range	Accuracy	Resolution	Data structure	Comments
BPM (position)	MEBT	5e10 - 2e14	.3 - 1000	+/- 0.5*apert	+/- .5mm	+/- .05mm	inside mini pulse	6, dual plane
	DTL	5e10 - 2e14	.3 - 1000		+/- .5mm	+/- .05mm		? , dual plane
	CCL-SCL	5e10 - 2e14	.3 - 1000		+/- 1mm	+/- 1mm		
	HEBT	5e10 - 2e14	.3 - 1000		+/- 1mm	+/- 1mm		20/38 each quad?, dual plane, each quad/doublet, dual plane
BPM (phase)	Ring-RTBT	5e10 - 2e14		+/- 1-20 mm	+/- 1 mm	0.15 mm	turn-by-turn	
	MEBT	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/- 2 deg	0.1 deg		6, 805MHz
	DTL	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/- 2 deg	0.1 deg		? , 805MHz
	CCL-SCL	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/- 2 deg	0.1 deg		? , 402.5MHz
IPM Wire	HEBT	5e10 - 2e14	.3 - 1000	+/- 180 deg	+/- 2 deg	0.1 deg		2?, 402.5MHz
	Ring	5e10 - 2e14		+/- 1-100 mm		1mm	turn-by-turn	three planes (H, V, 45 deg.) ?
	MEBT		.3 - 100	+/- 15mm		0.2mm		three planes
	DTL							
CCL-SCL			.3 - 100	+/- 15mm		0.2mm		three planes; each cryo.
			.3 - 1000	+/- 50mm		0.2mm		three planes
	HEBT			+/- 1-100mm		0.2mm	turn-by-turn steps	three planes
	Ring-RTBT	5e10 - 2e14						
Harp	DTL		.3 - 50	+/- 10 mm		1mm		after tank #3,#6; comissioning
	RTBT							
Misc. profile	D-plate		.3 - 1000					video fluorescence
	Ring							foil video
BLM	DTL-to-CCL		.3 - 1000	1-1000 rem/h	10% ?	1rem/h	100 mini pulses?	
	SCL-to-HEBT		.3 - 1000	1-1000 rem/h	10%	1rem/h	100 mini pulses?	
	Ring-RTBT	1e7 - 2e14		1-1000 rem/h	10%	1rem/h	average/turn-by-turn	
FBLM	DTL-to-CCL		.3 - 1000	1-1000 rem/h			inside mini pulse	fast; not calibrated
	SCL-to-HEBT		.3 - 1000	1-1000 rem/h			inside mini pulse	fast; not calibrated
	Ring			1-1000 rem/h			intra turn	fast; not calibrated
Current	MEBT-to-HEBT		.3 - 1000	0 - 52 mA	1%	.1%	inside mini pulse	
	Ring-RTBT	5e10 - 2e14		0.015-100A	1%	.1%	turn-by-turn	
Phase width	HEBT		.3 - 1000	0 - 600ps	15ps (5deg)	15ps (5deg)		??? LANL
	Ring				+/- 0.01			tune kicker/pick-up
Tune	HEBT		.3 - 1000	0 - 0.1mA	20%	.5mkA	each midi pulse	laser neutralization
	Ring			0 - 0.1 A	20%			BIG kicker/monitor
Beam-in-gap	HEBT		.3 - 10		10%			H & V
	Ring		.3 - 50		10%			H & V
Emitance	MEBT		.3 - 10					
	D-plate		.3 - 50					
e - detectors	Ring			2e8 - 2e11 (e-)	5%	1e8 (e-)	turn-by-turn	conspicuous locations
	WB BPM			+/- 1-60 mm?	+/- 1 mm	0.5 mm	turn-by-turn	100MHz BW
Laser wire	MEBT, DTL, ...?		.3 - 1000	+/- 15mm		.5mm	?	dual, three plane ?
HM monitor	Ring ?							"High moments" of transverse dis

Laser wire scanner for beam profile



Key Parameters



	Baseline	Back-up
Kinetic energy, E_k [MeV]	1000	975
Uncertainty, ΔE_k (95% probability) [MeV]	+/- 15	+/- 15
SRF cryo-module number	11+12	11+15
SRF cavity number	33+48	33+60
Peak gradient, E_p ($\beta=0.61$ cavity) [MV/m]	27.5 (+/- 2.5)	27.5 (+/- 2.5)
Peak gradient, E_p ($\beta=0.81$ cavity) [MV/m]	35 (+2.5/-7.5)	27.5 (+/- 2.5)
Beam power on target, P_{max} [MW]	1.4	1.7
Pulse length on target [ns]	695	699
Chopper beam-on duty factor [%]	68	68
Linac beam macro pulse duty factor [%]	6.0	6.0
Average macropulse H- current, [mA]	26	32
Linac average beam current [mA]	1.6	1.9
Ring rf frequency [MHz]	1.058	1.054
Ring injection time [ms] / turns	1.0 / 1060	1.0 / 1054
Ring bunch intensity [10^{14}]	1.6	1.9
Ring space-charge tune spread, ΔQ_{sc}	0.15	0.20

Summary



- SNS adopts a low-loss design philosophy
- Continuous design optimization to maximize performance
 - Adopted superconducting RF technology for the linac
 - Fully optimized the accumulator ring design to accept up to 1.3 GeV beam energy
- SNS is following a clear path towards a high-intensity (2×10^{14} at 60 Hz), high-power (2 MW) facility.

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